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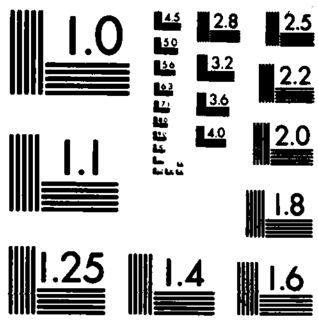

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Data from AFGL research flights were analyzed to determine the size spectra of snowflakes vs. temperature at levels just above the melting layer in stratiform clouds. Percentages of particles in various size ranges reveal a pattern of apparent snowflake aggregation and breakup which compare well with the mechanism proposed by Lo and Passarelli (1982).

In addition, a model of snowflake aggregation and breakup has been developed

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and run for various cloud parameters such as collection efficiency and cloud ice contents. The results of this analysis predict snowflake breakup temperatures quite close to those observed from the AFGL data.

FINAL REPORT

AFOSR-82-0173

AN INVESTIGATION INTO THE NATURE OF SNOWFLAKE AGGREGATION IN THE VICINITY OF THE MELTING LAYER IN STRATIFORM CLOUDS

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1 March 1983

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1. INTRODUCTION

The United States Air Force has recently expressed an interest in the cloud and precipitation microphysics in the vicinity of the melting layer in stratiform clouds. This interest arises from observations of nose cone erosion, and radio transmission difficulties in this area of the cloud.

The melting layer itself is defined by a "bright band" appearing on the RHI (range-height indicator) scope of weather radar. This bright band, first explained by Ryde (1946), is caused by a sharp increase in the radar reflectivity of precipitation hydrometeors as they melt. The acquisition of a liquid coating causes a sharp rise in the power of the returned signal. Since most of the precipitation melts at the same rate, this causes the appearance of a "bright band" on radar. The band is narrow in vertical extent, disappearing when the increase in fallspeed of the melted particles causes them to become less concentrated.

The degree of radar echo enhancement which is observed, however, is far greater than that which can be explained by melting alone. Wexler (1952) believes that the enhancement of the radar echo is caused by coalescence of ice crystals below the -3°C level. He also indicates that where little supercooled water is available, additional ice nuclei might come from shedding of splinters by dendritic snowflakes.

Mason (1955), Lhermitte and Atlas (1963), and Gunn and Marshall

(1958) have all indicated that aggregation of snow crystals is most likely responsible for the degree of radar echo enhancement seen in the bright band.

More recently, Lo and Passarelli (1982) have developed a new sampling method for studying the evolution of snowflake size spectra in stratiform clouds.

Basically, the method involves a slow, spiraling descent in an instrumented aircraft. The aircraft descends at approximately the same speed as the falling snowflakes, and is allowed to drift horizontally with the mean wind. Thus the aircraft remains in a 1-D region and essentially samples the same area of snow as it grows. This type of flight path has been termed the Advecting Spiral Descent (ASD).

Snowflake size spectra were measured continuously during the descent. These spectra took the exponential form

$$N_D = N_0 e^{-\lambda D} \tag{1}$$

where $N_D dD$ is the concentration in the size range (D, D+dD), and N_0 and λ are the distribution parameters (intercept and distribution slope, respectively).

By constructing relationships between N_0 and λ, Lo and Passarelli were able to determine a pattern of snowflake evolution involving depositional growth, aggregational growth, and breakup of aggregates.

It is their contention that the evolution of the snowflake size spectrum goes through three distinct stages. First, at levels above -15°C, or so, growth by deposition dominates. From approximately -15°C to -8°C, or so, the dominant mechanism is growth by aggregation. Below -8°C, or so, breakup of the aggregates is most probably occurring, as N_0 and λ become relatively stable. This seems logical in light of the fact that aggregates larger than, say, 7 mm are only rarely observed.

We have found that a different approach to the analysis of the data used by Lo and Passarelli yields further support for the aggregation/breakup mechanism in the near-melting layer vicinity.

2. OBJECTIVES

The initial objectives of this research were to continue the effort begun by the author while serving as an SCEEE/USAF Summer Faculty Research Fellow, and to refine the simple model of snowflake aggregation developed at that time by removing many of the arbitrary assumptions. Thus, an accurate picture of snowflake size distribution at the 0°C level could be inferred.

In addition, during the course of the research, it became evident that it might also be possible to use data from Air Force Geophysics Laboratory research flights to verify the accuracy of this simulated aggregation/breakup model. Subsequently, a second objective, that of confirming the existence of an aggregation and breakup cycle in snowflake evolution near the melting layer was added.

3. EXPERIMENTAL RESULTS

The database for the research was provided by the Air Force Geophysics Laboratory, AFSC, Hanscom AFB, MA. The AFGL's instrumented MC-130 cloud physics aircraft made a number of flights into stratiform clouds during the winter of 1979-80. Data from only two of these flights (Flight 80-10, 25 February; and Flight 80-11, 26 February) were used since these were the only flights which descended to altitudes near the 0°C level. Both of these flights were flown in the Advecting Spiral Descent pattern.

Data gathered from PMS 1-D cloud and precipitation probes were used to determine the size distribution of snowflakes at 1°C intervals of altitude separation as the aircraft slowly descended through the cloud. In all cases, we are referring to equivalent melted diameters.

It is assumed that at any given time, the size distribution of snowflakes takes the exponential form

$$N_D = N_0 e^{-\lambda D} \tag{2}$$

where $N_D dD$ is the number of particles in the size range $(D, D+dD)$, and N_0 and λ are the distribution parameters (intercept and distribution slope, respectively). To calculate the total particle concentration, N_t, at any given altitude, we integrate Eq. (2) from $D=0$ to $D=\infty$.

$$N_t = \int_0^\infty N_0 e^{-\lambda D} dD \tag{3}$$

The results of this integration at ambient temperatures from -30°C to -5°C are shown in Fig. 1 for both flights.

Examination of Fig. 1 reveals a number of interesting features. For flight 30-10, the general trend of the total particle concentration is upward, from a low concentration of 0.5 per cc at -28°C to a peak of 1.77 per cc at -7°C. For flight 30-11, however, the initial particle concentration is higher, 0.67 per cc, and actually decreases, reaching a value of 0.41 per cc at the -5°C level.

Both flights show a number of pronounced rises and falls in the total particle concentration, especially at temperatures warmer than -15°C. Since this is the area in which aggregation and breakup are to be expected, we have examined the distribution of particles by size range as a percentage of the total particle concentration. The results of this analysis are shown in Figs. 2a - 2f. The data terminate at the -5°C level since below this altitude, accretion of supercooled droplets is occurring to a large extent.

Table 1 shows correlation coefficients for the various size ranges of the two datasets, as well as that of the N_t curves. It is interesting to note that, while the total particle concentration curves are not well correlated at all (Correlation Coefficient=-0.144), when the data are compared in terms of percentage of total in a given size range, the correlation coefficients are extremely high, ranging from 0.949 to 0.724. In almost all cases, increases in the percentage of

particles of a given size range at any specific temperature occurring in Flight 30-10, are seen to occur at the same temperature in Flight 30-11. Similar behavior is seen for decreases in percentage. There is no reason to expect such a result, given that the total particle concentrations for the two flights are so dissimilar.

Also interesting is the fact that both sets of data, while starting out with very different size distributions near the -30°C level, seem to evolve to a similar size distribution (i.e. their distribution parameters are almost equal). This may indicate that the size distribution of particles entering the melting layer, in terms of percentage of the total concentration within a given size range, does not vary much from cloud to cloud, regardless of the distribution at higher levels in the cloud. Perhaps the mechanisms of aggregation and breakup serve to establish a size spectrum of particles entering the melting layer which is nearly constant (percentage-wise) from one cloud to the next.

A comparison of Figs. 2a and 2c illustrates the most striking example of the effect of aggregation and breakup on size distribution. It is observed that increases in the percentage of particles of diameter 2-3 mm are always accompanied by decreases in the percentage of particles smaller than 1 mm in diameter. Indeed, the curves for these two size ranges show an almost perfect negative correlation for both flights.

It would appear that aggregation of snowflakes begins with particles less than 1 mm in diameter, proceeds rapidly through the 1-2

mm diameter range and reaches the lower end of the 2-3 mm diameter range with no significant breakup. However, breakup appears to increase sharply as the particles approach 3 mm in diameter. Whenever breakup occurs, there is a sharp drop in the percentage of 2-3 mm diameter particles and an accompanying rise in the percentage of particles less than 1 mm in diameter. It is interesting to note that in Flight 30-10, breakup of 2-3 mm diameter (and larger) particles did not result in significant increases of 1-2 diameter particles; however, this was not the case in Flight 30-11, where increases in 1-2 mm diameter particles were seen during breakup of larger particles. This may be an effect related to the equalization process for the distribution as we near the melting layer. Indeed, the percentage of 1-2 mm diameter particles in Flight 30-10 remained essentially constant at 23-24% from the -13°C level down to -5°C, while the percentage of 1-2 mm diameter particles in Flight 30-11 did not become stable at this 23-24% level until -10°C.

Larger size ranges exhibited similar behavior (Figs. 2d-f), with periods of aggregation indicated by upswings in the percentage of large particles accompanied by sharp decreases in the number of small particles, and periods of breakup showing just the opposite behavior.

One of the initial problems encountered at the start of the research was that we had no idea what size the fragments of a broken-up snowflake would be. Our analysis of the data from these two flights seems to indicate that breakup of snowflakes will become a powerful mechanism when the flakes approach 3 mm in diameter. The breakups produce particles mainly smaller than 1 mm in diameter, with some

1-2 mm diameter particles produced as well. Most snowflakes reaching the critical size will break up (only 7-11% of the particles crossing the -5°C level were 4 mm in diameter or larger. In Flight 80-11, only 7% of the particles entering the melting layer were 4 mm in diameter or larger).

4. COMPARISON OF ASD DATA WITH THEORETICAL MODEL

A simple model of snowflake aggregation and breakup was developed prior to this research (Newman, 1981). This model contained a number of assumptions which have now been modified.

The basis for the model is the equation for snowflake aggregation given by Rogers (1979):

$$dm/dt = \bar{E}M\pi R^2 \Delta u \tag{4}$$

where dm/dt is the mass growth rate, $\bar{E}$ the mean collection efficiency, M the cloud ice content, R the radius of the collecting snowflake, and Δu the difference in fallspeed between the collecting snowflakes and the collected ice crystals. Mason (1971) has related the diameter, D, of stellar dendritic snowflakes to their mass by,

$$m = 0.027D^2 \tag{5}$$

and, substituting into Eq. (4) yields,

$$1/R \; dr/dt = 4.63\bar{E}M\pi\Delta u \tag{6}$$

The initial model assumed a constant value for Δu based on earlier research by Magono (1953) which indicated that snowflake fallspeed was essentially independent of size for dendritic flakes. However, Langleben (1954) has shown that snowflake fallspeed is a function of size such that,

$$u = 198.353R^{0.31} \tag{7}$$

We have further assumed that the collected ice crystals fall with constant speed of 30 cm/sec.

Thus we obtain the expression $(198.353R^{0.31} - 30)$ to be substituted for Δu, yielding,

$$dR/R = 4.63\bar{E}M\pi\,(198.353R^{0.31} - 30)dt \tag{8}$$

If we assume that M is relatively constant, and that the expression in parentheses is constant over a small interval of time, t, then the final aggregation equation will be,

$$R = R_0 \exp\left[4.63\bar{E}M\pi(198.353R_i^{0.31} - 30)t\right] \tag{9}$$

This equation can be solved for intervals of t=10 seconds. All that is required are values of $\bar{E}$ and M.

In the 1981 model runs, $\bar{E}$ values of 0.3, 0.9 and 1.0 were used. However, Passarelli (1978) has shown that there is a strong wake effect associated with falling dendritic snowflakes. This wake effect makes possible, values of $\bar{E}$ greater than unity. Passarelli found a value of 1.4 ± 0.6 to be in good agreement with observed aggregation rates. We have used this value of 1.4 in the model runs here.

In addition to the modifications in Δu, we have used the moist adiabatic lapse rate of -5.38°C/km in these runs. This is very close to the observed lapse rate for both AFGL flights. The earlier model had merely assumed lapse rates of -4, -5, and

-6°C/km. Thus many of the simplifying assumptions made in the earlier work have been modified or eliminated in favor of more recent observed data.

Table 2 shows the results of the model runs. Values of M were allowed to vary from 0.5 g/m^3 to 2.0 g/m^3. Note that for a cloud ice content of 1.5 g/m^3, the model predicts 3 occurrences of breakup at 3 mm diameter between -15°C and -5°C. These predicted breakups occur at -11.8°C, -8.6°C, and -5.4°C. These temperatures compare quite favorably with both AFGL flights, where breakup is apparently occurring at -13°C, -10°C, and -5°C. If the critical diameter is assumed to be as high as 4 mm, 3 breakups will occur at -12.0°C, -9.0°C, and -6.1°C for a cloud ice content of 2.0 g/m^3. Again, these predicted breakup temperatures compare favorably with observed data.

5. SUMMARY AND CONCLUSIONS

Lo and Passarelli (1982) have conducted experiments in stratiform clouds, dealing with snowflake size distributions. They have used a sampling method (the Advecting Spiral Descent) which follows the snowflakes down through the cloud at their approximate fallspeed.

They have defined three stages in the evolution of snow size spectra:

1) Depositional growth--occurring predominantly at temperatures colder than -13 to -16°C.
2) Growth by aggregation--occurring predominanatly at temperatures between -16 and -8°C.
3) Breakup of aggregates--which begins at about -8°C and continues down to the melting layer.

We have approached this problem in a somewhat different manner. By examining the total particle number concentration, and the percentages of this total of various size particles from less than 1 mm to more than 5 mm in diameter, we have been able to determine the altitudes at which aggregation and breakup are occurring.

Our analysis of the data clearly shows that when aggregation is occurring, the percentage of the total distribution of large particles increases at the expense of the smaller particles. Conversely, when breakup occurs, there is a sharp decrease in large particles, which is accompanied by a rise in the percentage of smaller particles. These fluctuations in size distribution are well explained by an

aggregation/breakup mechanism such as that proposed by Lo and Passarelli.

In addition, comparison of the apparent temperatures at which breakup is occurring in the cloud, to predicted temperatures from a simple model of aggregation and breakup shows a high degree of correlation. This would appear to provide further evidence for the existence of such a mechanism.

The remaining question is--does this mechanism actually occur? Unfortunately, there are not enough flight data available to provide a concrete answer. Further research will be needed to verify the existence of this mechanism in clouds, near the melting layer.

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TABLE 1

Size Range	Correlation Coefficient
All sizes	-0.1440
Percent 1 mm diameter	+0.9489
Percent 1-2 mm diameter	+0.8336
Percent 2-3 mm diameter	+0.9359
Percent 3-4 mm diameter	+0.8318
Percent 4-5 mm diameter	+0.3244
Percent 5 mm diameter	+0.7233

Table 1. Correlation coefficients for various size ranges between datasets 80-10 and 80-11

TABLE 2

Critical diameter (mm)	Cloud ice content (g/m^3)	Breakup temperature (C)
3	0.5	-5.5
	1.0	-10.3, -5.5
	1.5	-11.3,-8.6,-5.4
	2.0	-12.6,-10.2,-7.8,-5.5
4	0.5	--
	1.0	-9.1
	1.5	-11.1,-7.1
	2.0	-12.0,-9.0,-6.1

Table 2. Predicted breakup temperatures for critical diameters of 3 and 4 mm at various cloud ice contents.

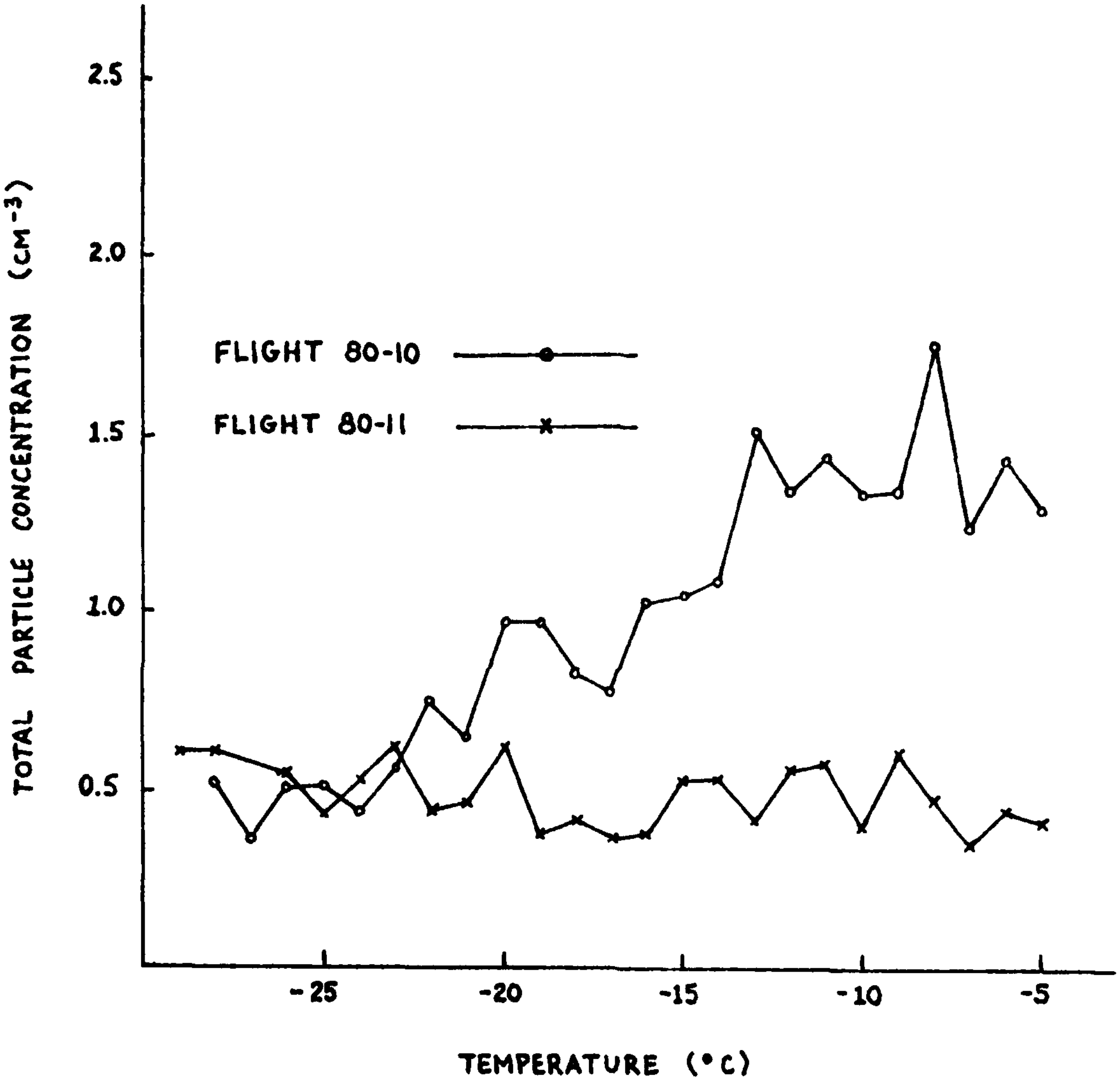

Fig. 1. Total particle concentrations vs. temperature

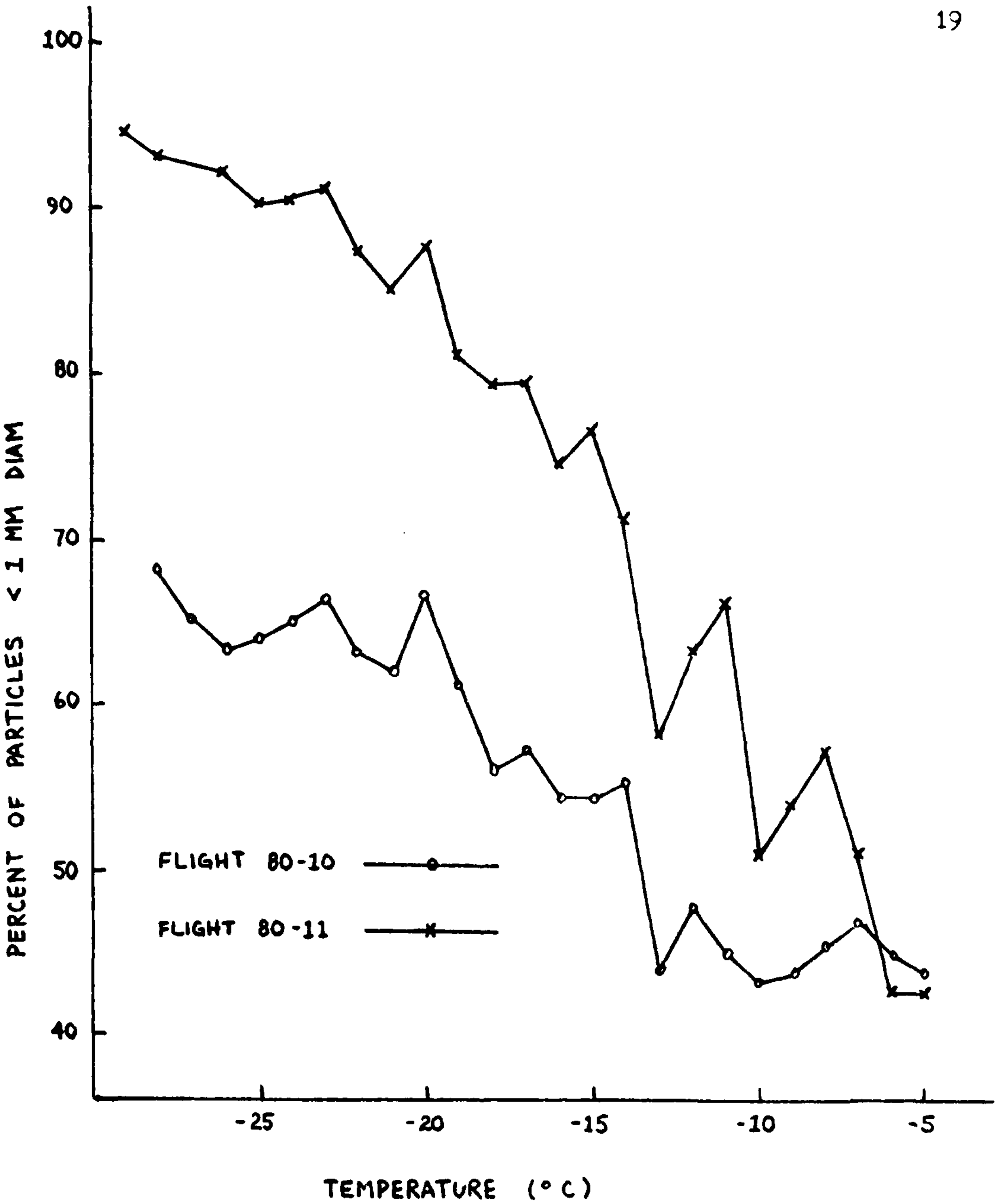

Fig. 2a. Percent of particles < 1 mm diameter vs. temperature

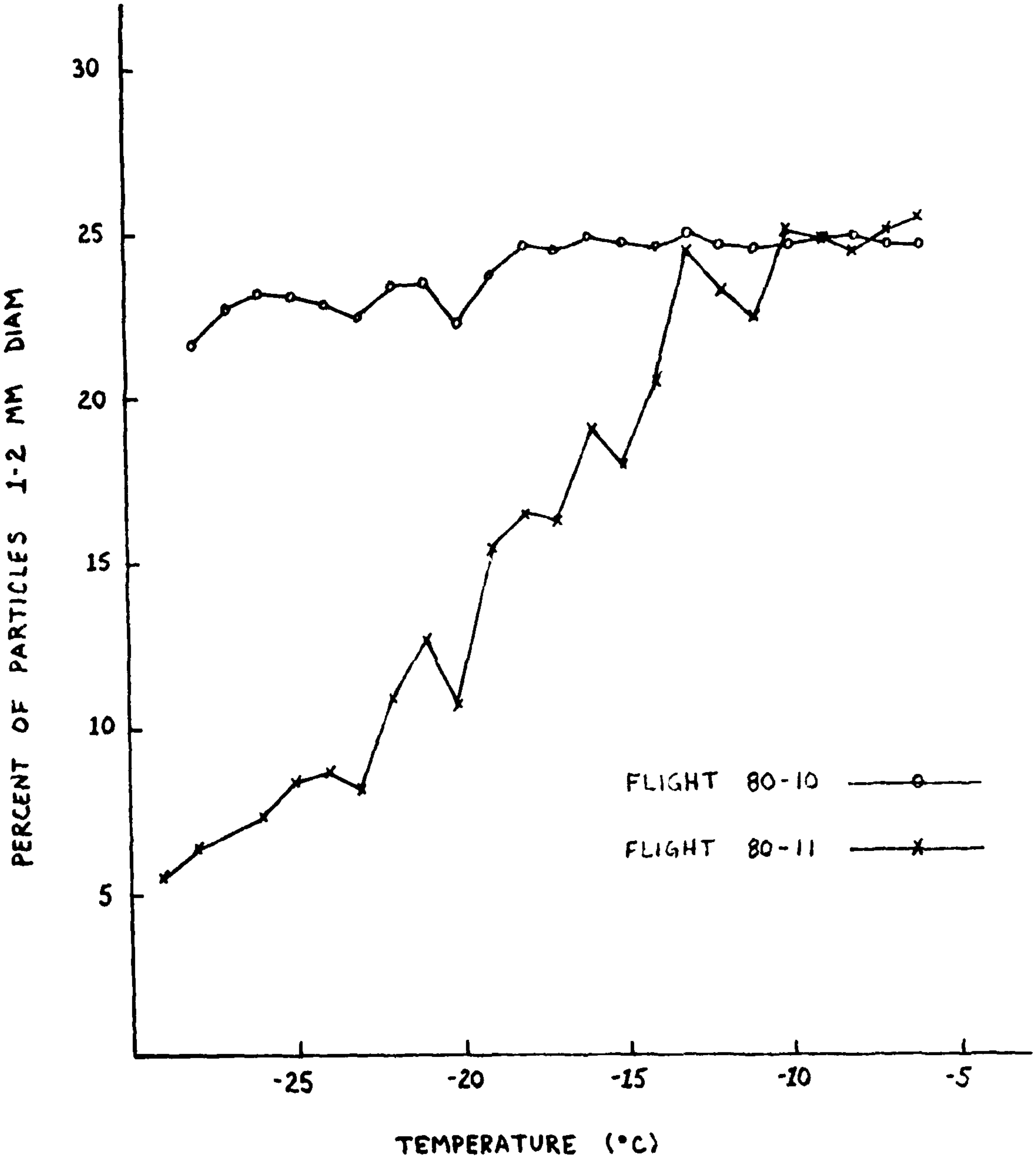

Fig. 2b. Percent of particles 1-2 mm diameter vs. temperature

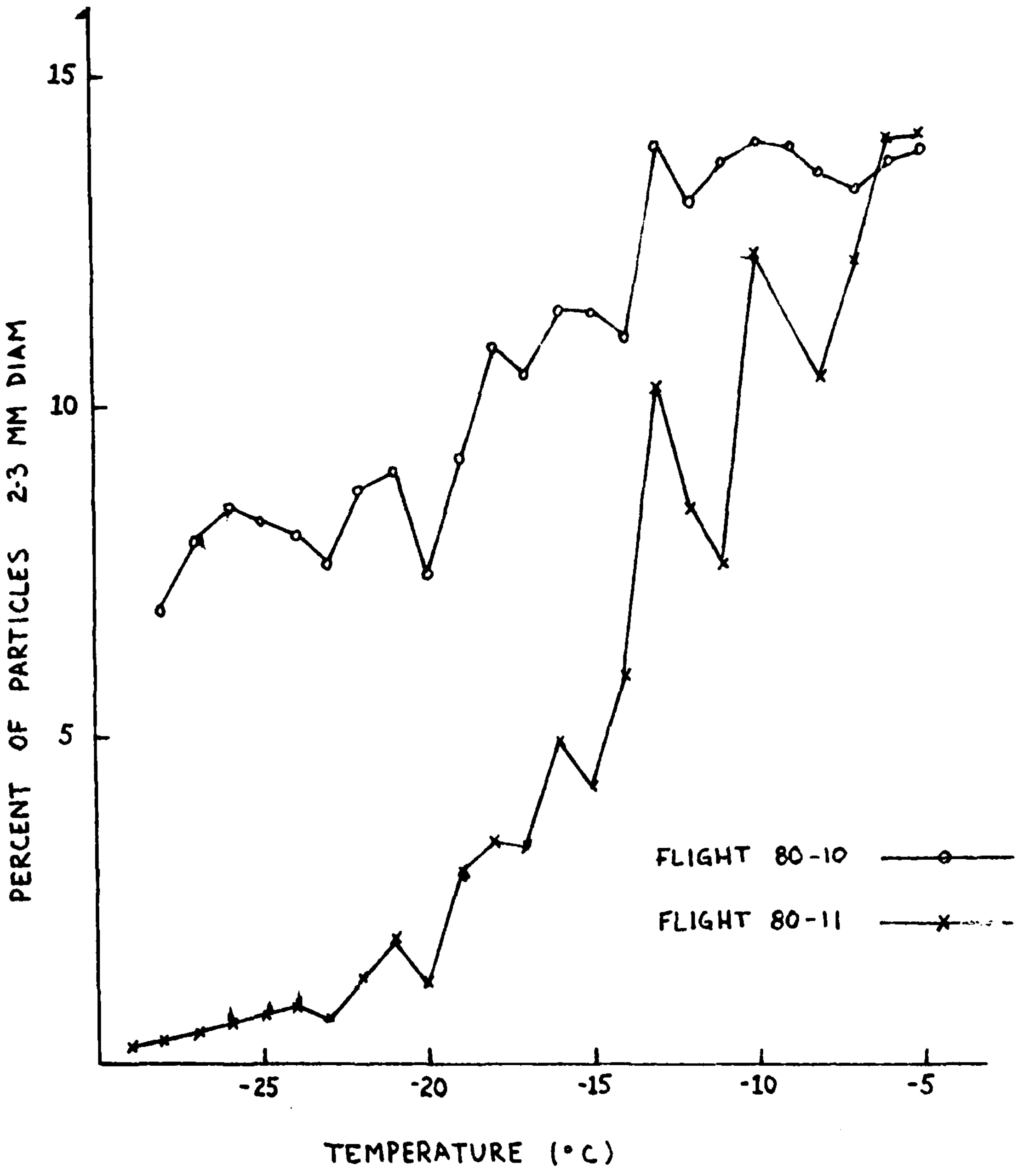

Fig. 2c. Percent of particles 2-3 mm diameter vs. temperature

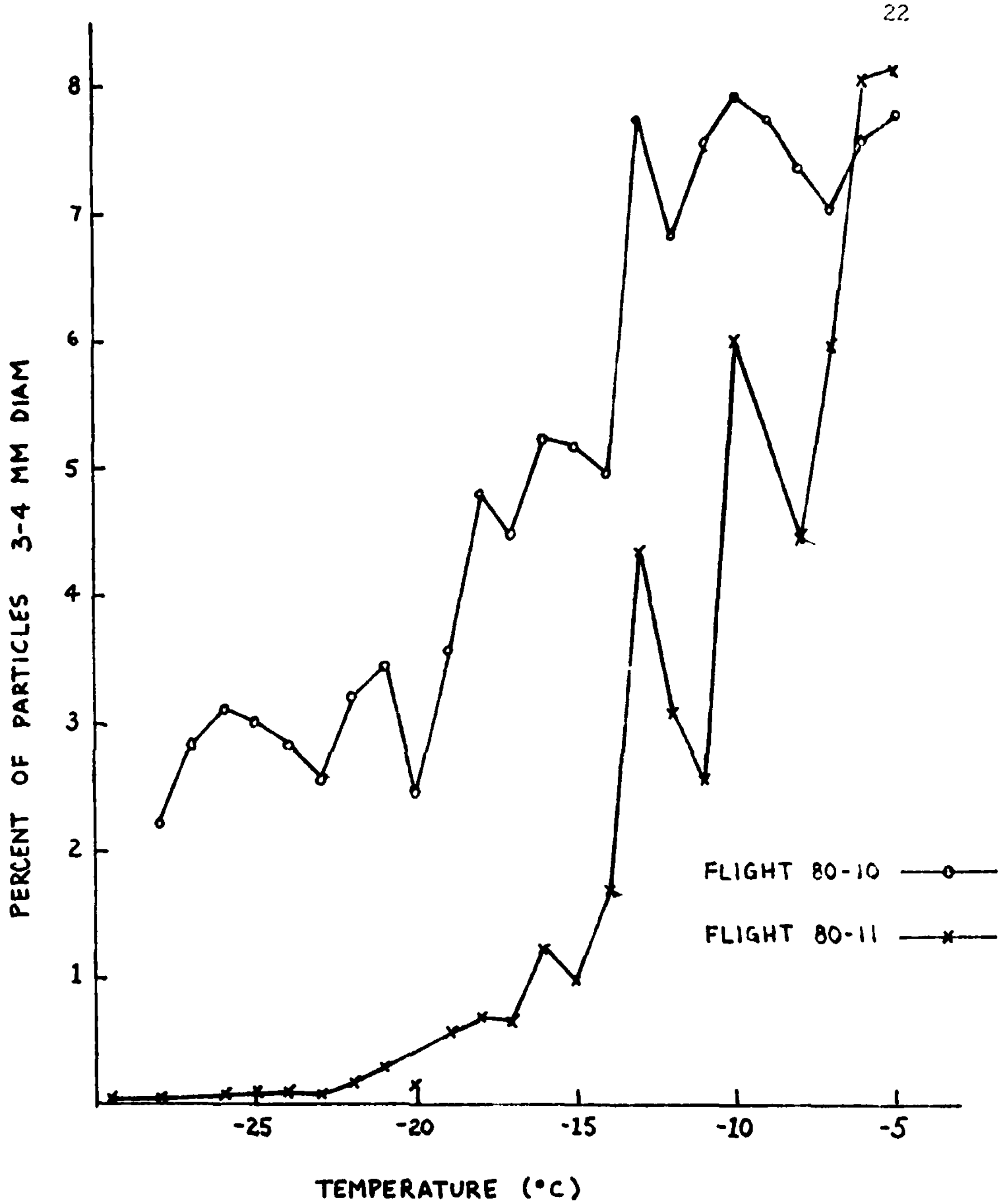

Fig. 2d. Percent of particles 3-4 mm diameter vs. temperature

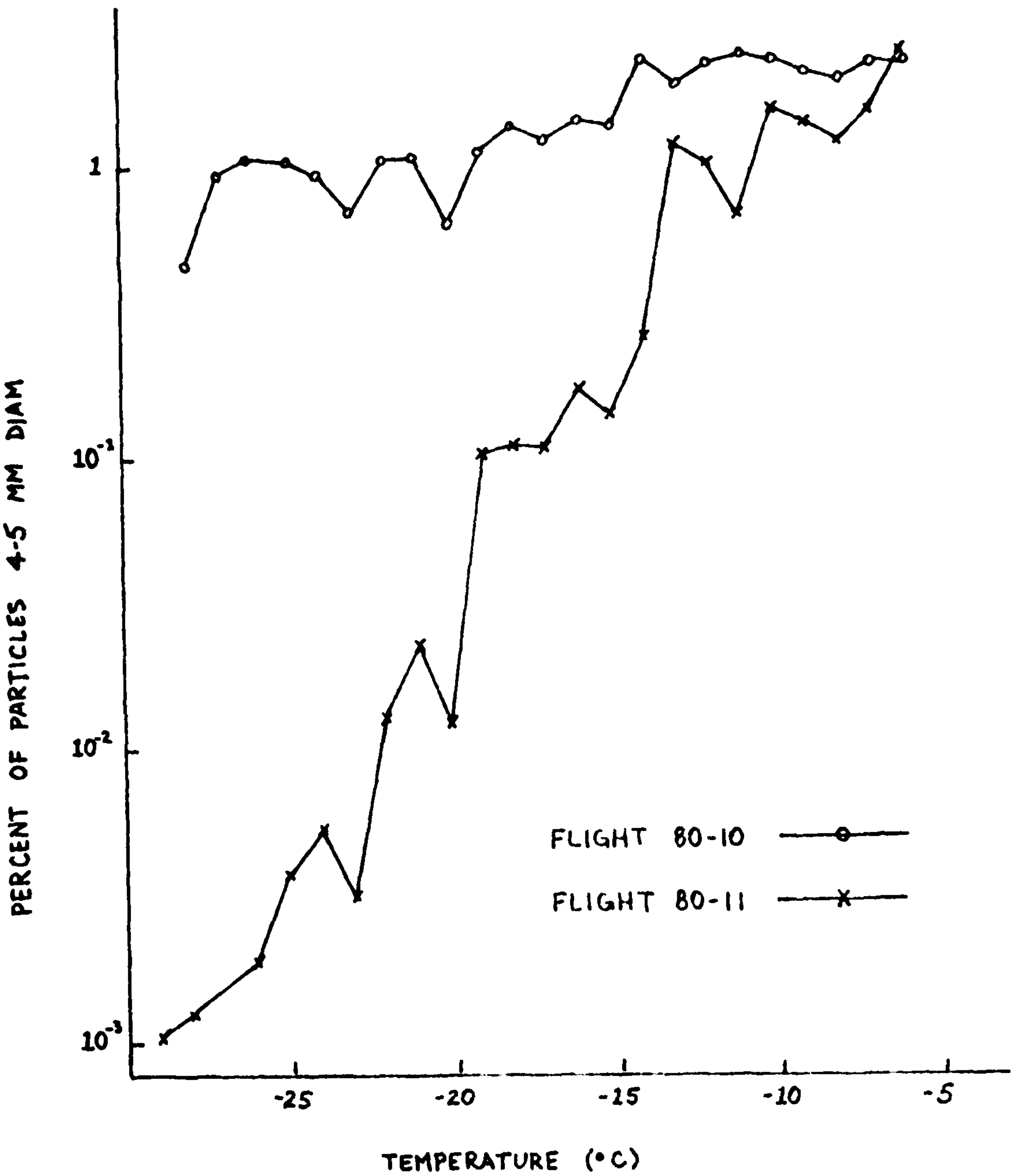

Fig. 2e. Percent of particles 4-5 mm diameter vs. temperature

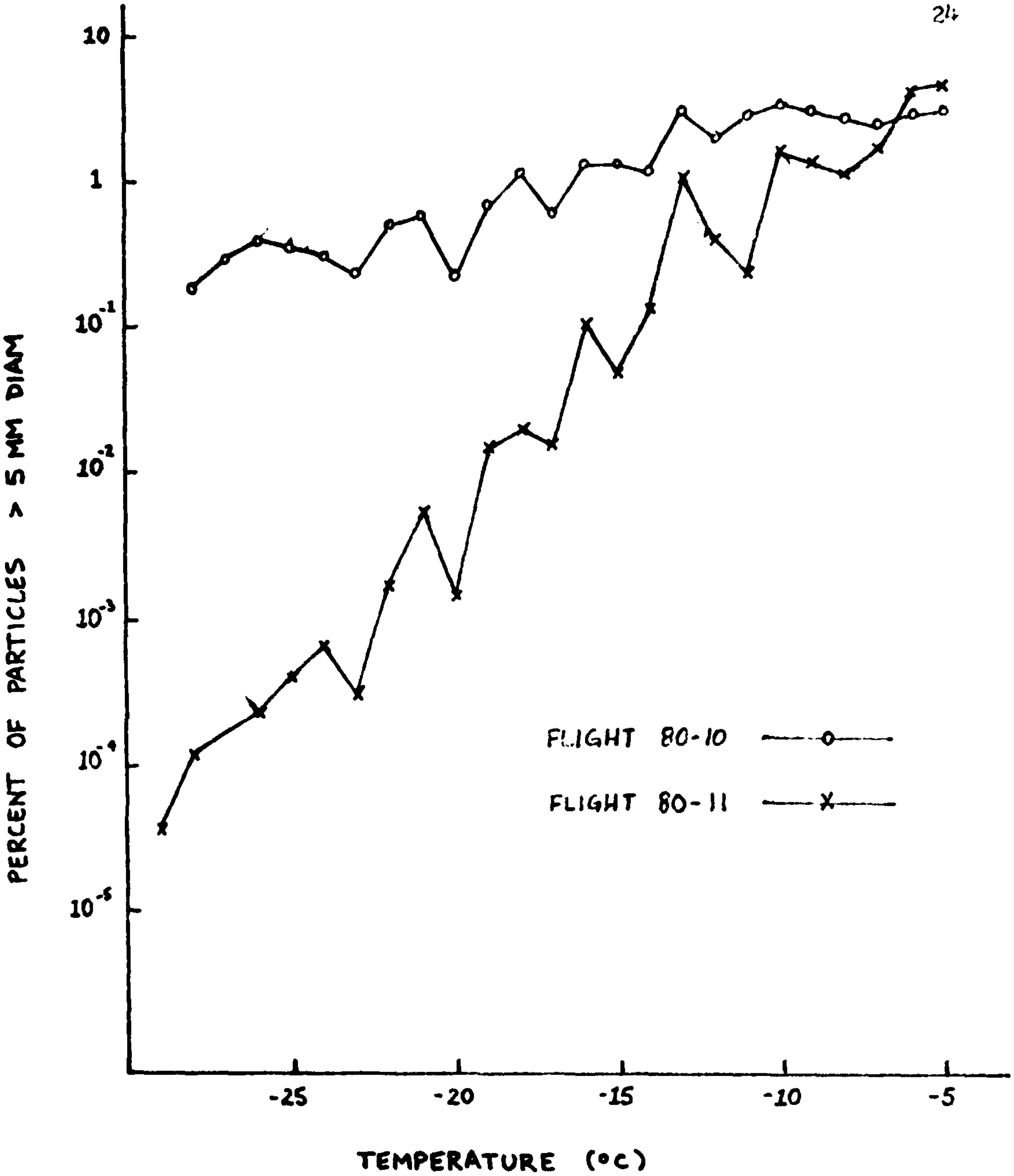

Fig. 2f. Percent of particles > 5 mm diameter vs. temperature

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